

# Supersymmetry versus black holes at the LHC

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## Abstract

Supersymmetry and extra dimensions are the two most promising candidates for new physics at the TeV scale. Supersymmetric particles or extra-dimensional effects could soon be observed at the Large Hadron Collider. We propose a simple but powerful method to discriminate the two models: the analysis of isolated leptons with high transverse momentum. Black hole events are simulated with the CATFISH black hole generator. Supersymmetry simulations use a combination of PYTHIA and ISAJET, the latter providing the mass spectrum. Our results show the measure of the dilepton invariant mass provides a strong signature to differentiate supersymmetry and black hole events at the Large Hadron Collider. Analysis of event-shape variables and multilepton events complement and strengthen this conclusion.

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## I. INTRODUCTION

After more than a decade of intense work, CERN's Large Hadron Collider (LHC) beam commissioning to 7 TeV is scheduled for July 2008 [1]. The primary purpose of the LHC is to provide experimental evidence for the Higgs particle and look for new physics beyond the Standard Model (SM). Supersymmetry (SUSY) [2] is one of the best and most studied candidates for physics beyond the SM. It provides an explanation for the Higgs mass problem and a candidate for cold dark matter and unification of low-energy gauge couplings by introducing superpartners to SM fields. Alternatives to SUSY include extra-dimensional models such as large extra dimensions [3], warped braneworlds [4] or universal extra dimensions [5]. In these models, gravity becomes strong at the TeV scale, where radiative stability is achieved. The most astounding consequences of TeV-scale Planck mass is perhaps the production of Black Holes (BHs) in particle colliders [6] and cosmic ray showers [7].

At a time when the LHC is becoming a reality, there is a pressing need to provide the scientific community with tools to extract physical information from the forthcoming data. The first step in the LHC analysis pipeline is the identification of strong experimental signatures to distinguish the various proposals for physics beyond the SM. Comparisons of SUSY and extra dimensions/little Higgs models have been recently investigated by various authors [8, 9]. Here, the focus is on the difference between SUSY and BH events. Our main result is that the measure of the dilepton invariant mass is a very strong discriminator between SUSY and BHs. The message of this paper is thus straightforward: Take LHC data, select dilepton events with high transverse momentum ( $P_T$ ), measure the invariant mass, rule out either SUSY or BHs. This procedure is discussed in detail below.

## II. SUPERSYMMETRY AND BLACK HOLES AT THE LHC

According to the Minimal Supersymmetric extension of the Standard Model (MSSM) [2], all SM fermions (bosons) must have a bosonic (fermionic) partner. Since we do not observe superpartners of SM particles at low energies, SUSY must be a broken symmetry. A method of SUSY breaking mediated by gravitational interactions is supergravity (SUGRA). In its minimal version, mSUGRA is determined by a point in the five-dimensional moduli space

with parameters  $m_0$  (the common scalar mass at  $M_{GUT}$ ),  $m_{1/2}$  (the common gaugino mass at  $M_{GUT}$ ),  $A_0$  (the common trilinear coupling at  $M_{GUT}$ ),  $\tan \beta$  (the ratio of the vacuum expectation values of the two Higgs fields), and  $\mu$  (the sign of the Higgsino mass parameter). Without loss of generality, we choose  $m_0 = 100$  GeV,  $m_{1/2} = 300$  GeV,  $A_0 = 300$ ,  $\tan \beta = 2.1$  and  $\mu = +1$  as SUSY benchmark when comparing SUSY to BH events. (This is known in the literature as SUSY point A [10] or point 5 [11]. The choice of a different SUSY point does not affect the results of our analysis [12].) SUSY interactions conserve R-parity [2]. R-parity conservation implies that SUSY particles are always pair produced at the LHC and that SUSY events end with the production of a stable colorless and chargeless lightest SUSY particle (LSP). In the analysis below, SUSY events are simulated by generating mass spectra with ISAJET (ver. 7.75) [13] and interactions with PYTHIA (ver. 6.406) [14]. All MSSM processes have been included except Higgs production from SM interactions.

Numerous studies have focused on BH signatures at the LHC. (See Ref. [15] for reviews and details.) A quick look at BH production in colliders reveals the following. BHs are formed when two partons interact with impact parameter less than the Schwarzschild radius corresponding to their center-of-mass energy. The production cross-section is approximately equal to the geometrical cross section of the event. After its formation, the BH decays semiclassically through Hawking radiation. At the end of the Hawking decay quantum gravity effects lead to the formation of stable remnant or the disintegration into a number of hard quanta. Most of the particles are believed to be emitted on the brane [16]. (See also Ref. [17].) Simulations of BH events are carried out with the CATFISH generator [18]. We choose a conservative benchmark model for BH events with six extra dimensions, fundamental Planck scale 1 TeV, minimum BH mass at formation of 2 TeV, BH mass at the end of the Hawking phase of 1 TeV and two final hard quanta [12].

### III. ANALYSIS OF DILEPTON EVENTS

The measure of the dilepton invariant mass allows the discrimination of BH and SUSY events as follows. Our analysis is based on opposite sign, same flavor (OSSF) dileptons [11].

In SUSY, the dominant source of dilepton events is the process

$$\begin{array}{c} \tilde{\chi}_2^0 \rightarrow l^\pm \tilde{l} \\ \downarrow \\ \tilde{l} \rightarrow l^\mp \tilde{\chi}_1^0, \end{array}$$

which has a branching ratio of 27% at LHC point 5. (The process  $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 h$  counts for 68%.) [19]. The dilepton invariant mass is defined as

$$M_{ll} = \sqrt{(E_{l^+} + E_{l^-})^2 - (\mathbf{p}_{l^+} + \mathbf{p}_{l^-})^2}. \quad (1)$$

Since the LSP is undetectable, the SUSY dilepton invariant mass distribution has an edge at [11]

$$M_{ll}^{max} = m_{\tilde{\chi}_2^0} \left[ \left( 1 - \frac{m_{\tilde{l}}^2}{m_{\tilde{\chi}_2^0}^2} \right) \left( 1 - \frac{m_{\tilde{\chi}_1^0}^2}{m_{\tilde{l}}^2} \right) \right]^{\frac{1}{2}} \sim 100 \text{ GeV}. \quad (2)$$

Dilepton events from BHs are not originated by a single process. Most of isolated high- $P_T$  leptons come directly from the BH, from the decay of a  $Z_0$  boson, or from a top quark. (In the latter process, the preferred channel for the dilepton event consists of one lepton from the BH and one from a top quark.) Therefore, the dilepton invariant mass distribution (1) has no endpoint. Moreover, since the dominant decay mode of a top quark is into hadrons [20], and the branching ratio of  $Z_0$  into leptons is  $\Gamma(l^+ l^-)/\Gamma_{tot} \sim 3.37\%$  [20], the rate of BH OSSF dilepton events is expected to be smaller than in SUSY. To compare the invariant mass in the two models, we select isolated events with high  $P_T$ . We impose the following cuts on leptons [11]:

- Transverse momentum  $P_T \geq 15 \text{ GeV}$ ;
- Pseudorapidity [14]  $\eta_l < 2.5$ ;
- Isolation cut  $p_T < 7 \text{ GeV}$  in a cone of  $R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.2$ , where  $\phi$  is the azimuthal angle.

Figure 1 shows the invariant mass distribution for 1000 SUSY and BH OSSF dilepton events. (The rate of BH-to-SUSY dilepton events at fixed luminosity is about 1:5.) As was expected, the SUSY invariant mass distribution shows a sharp edge at  $\sim 100 \text{ GeV}$ . The BH invariant

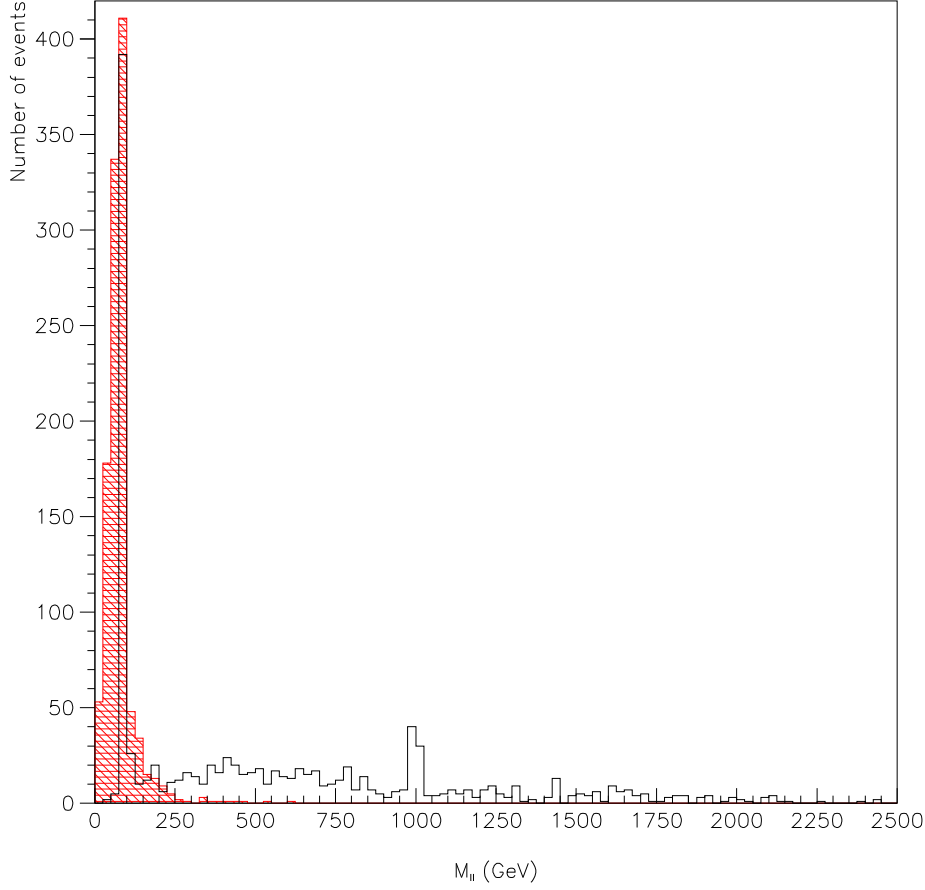


FIG. 1: Invariant mass distribution (in GeV) for 1000 SUSY (shaded red histogram) and 1000 BH OSSF dilepton events. The SUSY distribution shows the typical endpoint due to the presence of the LSP. The high- $P_T$  tail of the BH distribution is originated by uncorrelated lepton pairs emitted by the BH during the Hawking evaporation phase.

mass distribution shows a peak at  $\sim 90$  GeV, a second smaller peak at 1 TeV and a tail at high  $P_T$ . The first peak is due to dilepton events from single  $Z_0$  bosons which are directly emitted by the BH. This is the dominant channel of OSSF dilepton production in BH events. The peak at 1 TeV is due to dileptons emitted at the end of the Hawking phase [18]. The BH mass and the number of final hard quanta at the end of the Hawking phase have been chosen to be 1 TeV and 2, respectively. Since the BH at the end of the Hawking phase is expected to be electrically neutral, isolated dilepton events can occur, for example, when the two final quanta are opposite sign leptons or a  $t\bar{t}$  pair. This peak is expected to be smeared out in a more realistic description of the final BH phase [12]. The high- $M_{ll}$  tail of

the distribution is originated by pairs of uncorrelated leptons from the BH.

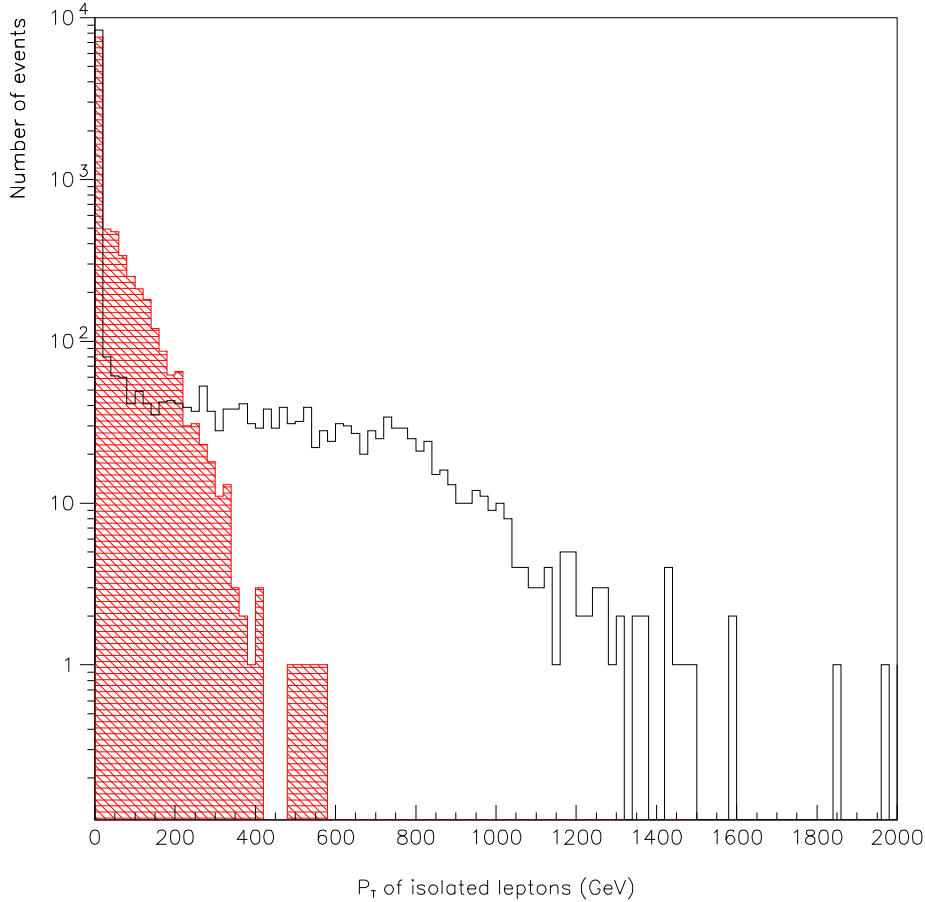


FIG. 2: Transverse momentum distribution (in GeV) for 10,000 isolated high- $P_T$  leptons in SUSY (shaded red histogram) and BH models. High- $P_T$  isolated leptons from BH events are mostly emitted by the BH during the Hawking phase and have large transverse momentum.

The distribution of high- $P_T$  isolated leptons can also be used to discriminate SUSY and BH events (Fig. 2). Isolated leptons which are emitted from the BH have higher  $P_T$  than SUSY leptons. Simulations show that a BH with mass  $M_{BH} \sim \text{few} \times \text{TeV}$  emits few quanta during the Hawking evaporation phase, with an average energy of  $E \sim M_{BH}/\text{few} \sim \text{TeV}$  [18].

Another powerful discriminator is counting the number of isolated, high- $P_T$  leptons (of any flavor). Figure 3 shows that SUSY events are capable of producing up to five isolated leptons from the cascade decay of heavy sparticles. Presence of two  $\tilde{\chi}_2^0$ 's in an event can produce four isolated leptons and three leptons can be produced by a  $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$  event [21].

Multilepton events are rare in BH decays, where the probability of emission of more than three isolated leptons in the Hawking phase is essentially zero. Although isolated multilepton events are rare in both models, there is very little background. Therefore, the number of isolated leptons and their  $P_T$  can be successfully used as SUSY/BH discriminators. Figure 4 shows a scatter plot of high- $P_T$  electrons ( $e^-$  or  $e^+$ ) vs. high- $P_T$  muons ( $\mu^-$  or  $\mu^+$ )

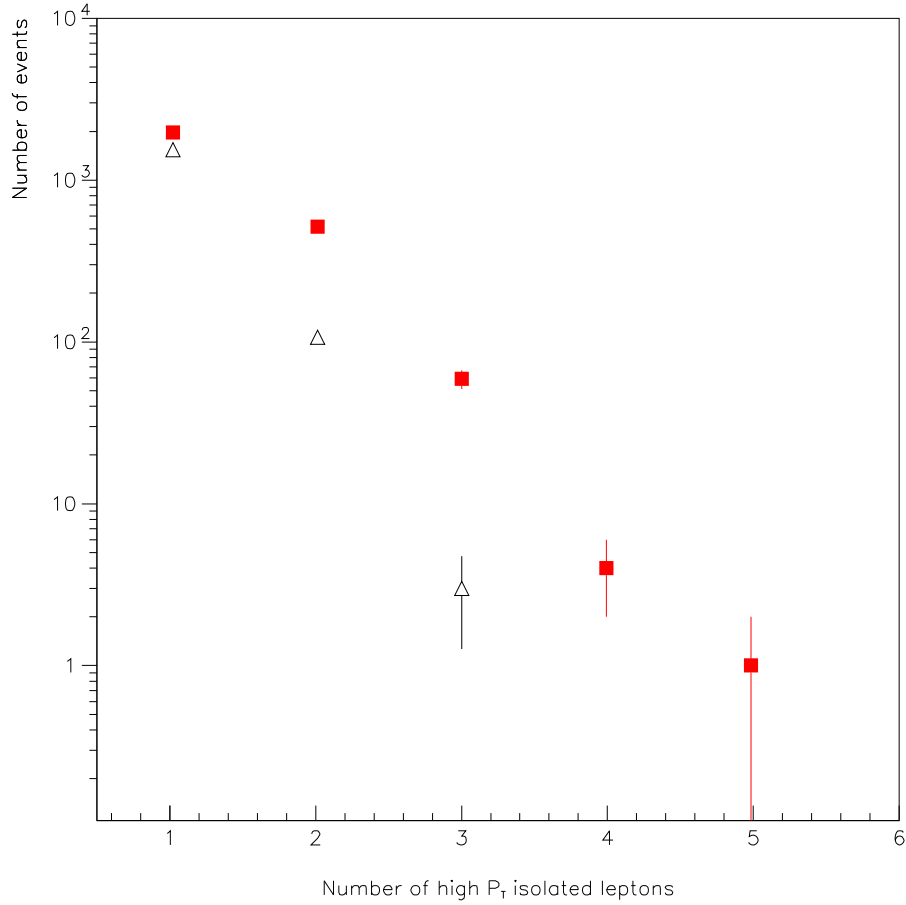


FIG. 3: Number of high- $P_T$  leptons for SUSY and BH models (10,000 events). The number of BH events (black open triangles) with three isolated leptons is smaller than the number of SUSY events (red filled squares) by a factor  $\sim 20$ . The probability of producing BH events with four or more leptons is virtually zero.

for SUSY and BH events. SUSY isolated leptons have on average lower  $P_T$  compared to BH isolated leptons.

Dilepton events with same sign and/or opposite flavor leptons can also be used as discriminators. The “democratic” nature of BH decay makes events with same/opposite flavor leptons roughly equally probable, whereas branching ratios of SUSY events favor same-flavor

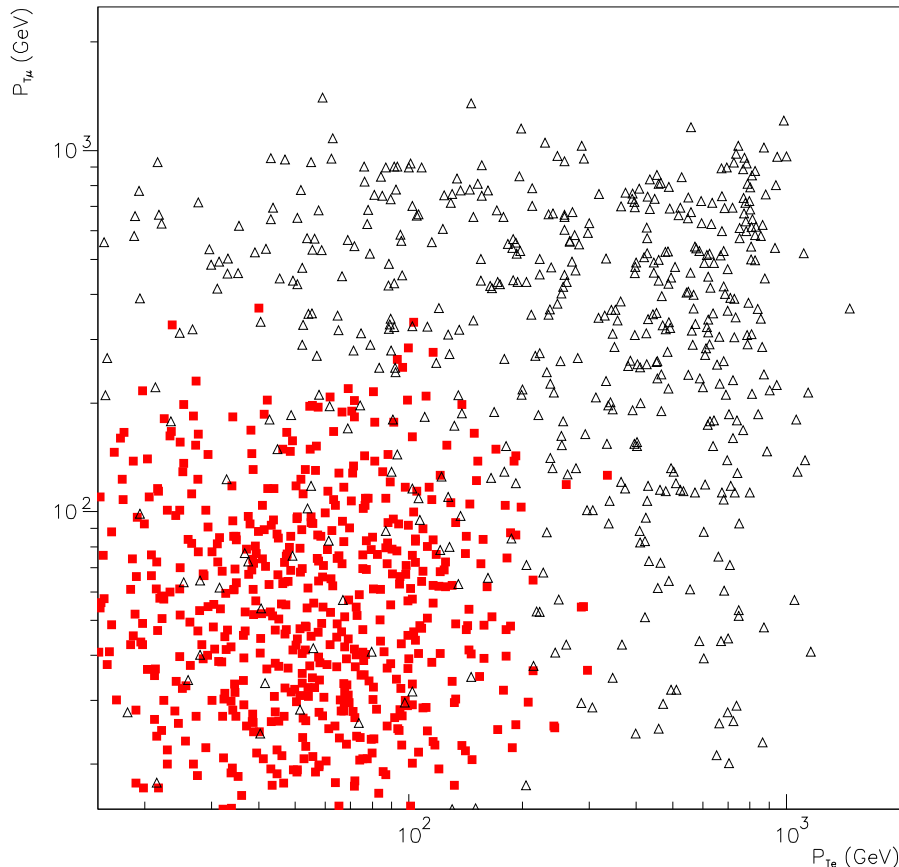


FIG. 4: Scatter plot of transverse momentum for approximately 500 isolated opposite-flavor dilepton events ( $P_{Te}$  vs.  $P_{T\mu}$ ) for SUSY (red filled squares) and BH (black open triangles). Leptons in BH events are characterized by larger value and larger spread of their transverse momentum.

dileptons. Table I shows the branching ratios of same-/opposite-sign, same-/opposite-flavor isolated dilepton events for SUSY and BH processes. The dominant channel is the OSSF channel for both models. However, SUSY and BH events can be easily discriminated by comparing the rate of same-flavor events to the rate of opposite-flavor events.

Analysis of event-shape variables can be used to complement the above results. BH events are expected to be more spherical than SUSY events because of the isotropic nature of Hawking radiation [18]. This statement can be made quantitative by looking at the second Fox-Wolfram moment  $R_2$  [14] (see Fig. 5). SUSY events show a sharp peak at  $R_2 \sim 0.85$  whereas the BH events are characterized by a flatter distribution in the range  $0.65 \lesssim R_2 \lesssim 0.9$ . Event-shape variables alone cannot effectively discriminate between SUSY



TABLE I: Branching ratios of high- $P_T$  isolated dileptons for SUSY and BH models. 21,000 and 100,000 events were simulated in the two cases, respectively, yielding approximately 1000 dilepton events. OS(SS) stands for opposite(same) sign and OF(SF) denotes opposite(same) flavor.

High $P_T$ isolated dileptons	$SUSY$ %	$BH$ %
OSSF	768 73 523 50	
SSSF	65 6 103 10	
OSOF	169 16 341 32	
SSOF	52 5 87 8	

and BHs. However, their knowledge may prove useful when combined with the analysis of dilepton events.

#### IV. CONCLUSIONS

The LHC should be able to detect SUSY or large extra dimensions, if they exist. In this letter we have presented a powerful way to differentiate these two models based on dilepton events. Isolated dileptons from SUSY and BH processes behave very differently. While SUSY dileptons with high  $P_T$  are characterized by a sharp endpoint of the invariant mass distribution well below 1 TeV, BH dileptons can have invariant mass as large as several TeV. This result can be complemented by looking at the number and flavor of isolated leptons and event-shape variables. A simple analysis of high- $P_T$  isolated dilepton events will thus allow the LHC to discriminate, and possibly rule out, either SUSY or BH formation at the TeV scale.

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[1] <http://lhc.web.cern.ch/lhc/>

[2] See, e.g. S. P. Martin, “A supersymmetry primer,” arXiv:hep-ph/9709356.

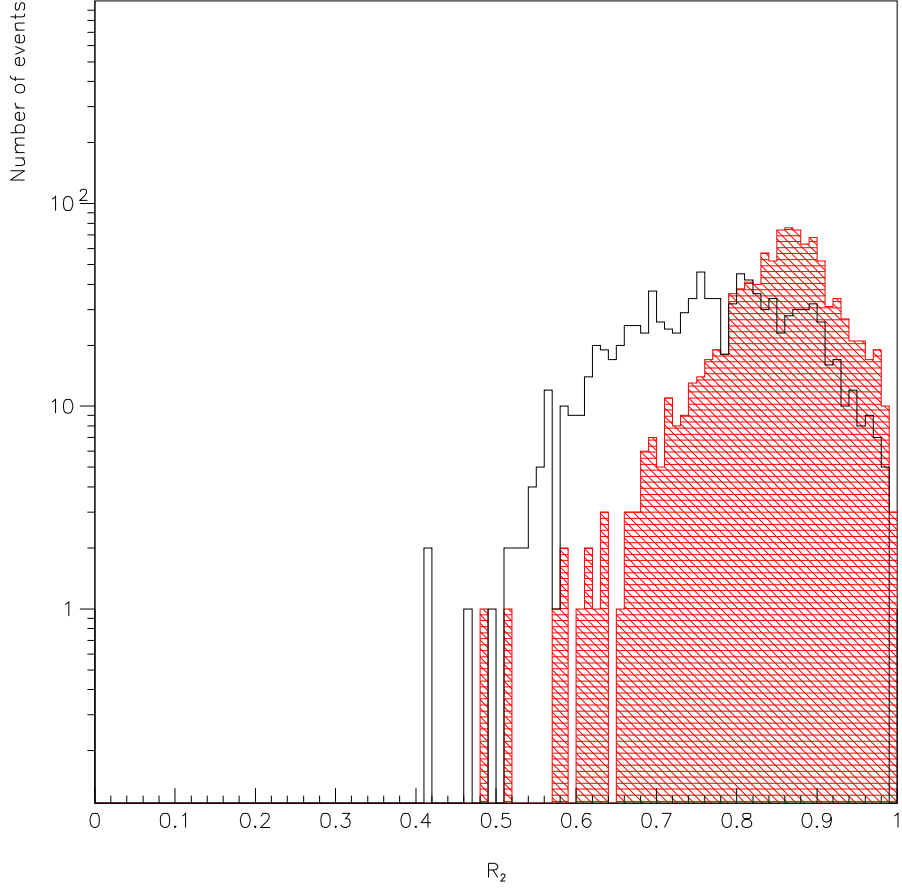


FIG. 5: Second Fox-Wolfman moment distribution for 1000 SUSY (shaded red histogram) and BH isolated OSSF dilepton events.

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